DESIGN AND FABRICATION OF MICROMACHINED INTERNAL COMBUSTION ENGINE AS A POWER SOURCE FOR MICROSYSTEMS

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ABSTRACT

In this paper, a new micromachined reciprocating engine utilizing the pressure built up by combustion has been designed and fabricated. As a basework for development of micromachined engines, initial combustion experiments have been performed using a microscale combustor made by conventional machining. From these experiments, a new micromachined engine has been proposed and its proper chamber dimension has been determined for stable ignition and flame propagation. The proposed engine has a unique structure simplified from the general reciprocating engines in order to make it suitable to be fabricated using MEMS processes and applied for movable microsystems. We have demonstrated actual one-shot combustion test of the fabricated prototype microengine and generation of a movable power using premixed hydrogen and air fuel.

INTRODUCTION

Recently, advancement of micromachining technologies has opened the new possibilities to be applied for the movable microsystems such as micro-robots, pico-satellites, and micro-air-vehicles. Supplying power to such tiny devices has been a major technological challenge since the power requirement of these systems exceeds what the conventional batteries can provide over an extended operation. An alternative power source is utilizing conventional fuels used in combustion driven power sources. The energy density of these liquid fuels is far higher than batteries, even allowing relatively low thermal efficiency and forgiving additional device requirements for the conversion of the thermal energy into power. Currently, a few research projects are attempting to harness the high energy density of fuels in microscale. Micro-gas-turbine [1], solid-propellant-microrocket [2], and rotary-engine [3] are a few examples among those under development. In this paper we report our first attempt to realize a micro combustion engine using MEMS technology. We will discuss the general issues related with the design of each component of the micro engine including material selection, combustion chamber scaling, and leakage in moving parts as well as report the fabrication processes in detail, followed by initial combustion tests of the fabricated micro engine.

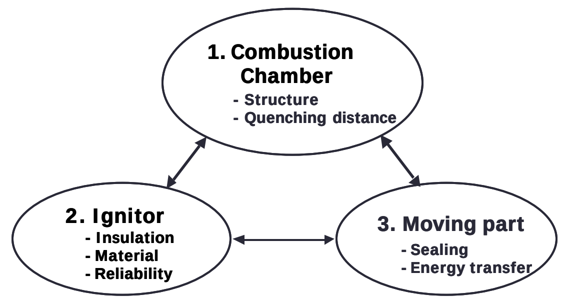

Figure 1. **Components issues of micro combustion engine**

COMPONENTS ISSUES

The major components of micro combustion engine are classified into three parts as shown in Fig. 1: 1) combustion chamber; 2) ignitor; and 3) moving parts. Developing these components in micro scale faces many difficulties and obstacles.

Combustion chamber – Quenching distance

One of the major problems in the development of a micro engine is to obtain genuine combustion in a limited volume of the combustor. Existing literatures on combustion do not provide sufficient understanding of the phenomena in a volume that is comparable to a laminar flame thickness. Scaling down of the combustion chamber may significantly increase heat loss, so that it may result in quenching the flame. Therefore, as a preliminary work on micro engine design, geometric limitation of combustor dimension should be extensively examined.

Ignitor - Breakdown voltage

High electric field is needed to ignite a micro combustion engine. In this condition, electrical isolation between two electrodes and reliability of electrodes against erosion while discharging has to be guaranteed. To reduce the erosion of electrodes, applied voltage between the electrodes should be minimized and robust material has to be selected for electrodes.

Moving parts – Leakage path

Micro combustion engine is a device which converts the chemical energy into mechanical energy. Therefore, it should have moving parts and the leakage path between moving parts and static parts does always exist. Especially, if one transfer power from the moving parts to any external apparatus, the leakage path cannot be avoided.

DESIGN GUIDELINES OF MICRO ENGINE

Selection of Materials

It is so important to choose the proper materials for each component of micro engine. For spark plugs, one must consider melting point of the material, material sputter resistance, and oxidation characteristics. Nickel (Ni) can be a good candidate for spark plugs [4]. It has a high melting point, 1453°C, and can be easily deposited in relatively large volumes by electroplating which is well established for microfabrication.

The most important criteria in material selection for combustion chambers, pistons, piston cylinders and covers of the engine are low thermal conductivity for minimizing heat loss and electrical insulation for spark plugs. We have chosen photosensitive glass (Mikroglas Co., Foturan glass) as a material for the micromachined engine body because it can provide good electrical insulation, maintain good heat isolation, provide easy observation of combustion and actuation due to its transparency, and allow to build flexible microstructures by using conventional microlithography. Utilizing photosensitive glass enables to reduce the process steps required for insulation of high ignition voltage and to produce high aspect ratio engine structures.

Scaling combustor dimension

Figure 2 shows an experiment set up to investigate combustion phenomena in micro scale. This variable-depth combustor has a cylindrical cavity of 15*mm* in diameter and chamber height varied from 0.4*mm* to 4*mm*. A hydrogen and air premixture gas has been used as a fuel. This is because hydrogen has low quenching distance and low ignition energy among available fuels including hydrocarbons. Ignition was done by coil-induced high voltage and ignition energy provided was about 1.7~1.8*mJ*. Maximum chamber pressure created by combustion of the fuel has been measured as a function of chamber height for various initial pressures in Fig. 3. A chamber height of 0.61*mm* corresponds to absolute quenching distance of the fuel [5] because definite ignition and pressure rise can be observed. With the help of theoretical model [6], combustion efficiency can be estimated for each test case as shown in Fig. 4. Combustion efficiency is defined by the ratio of reversible work obtained by the fuel to ideal heat produced by hydrogen contained in the burnt volume. Here, we can confirm that, for chamber heights less than 2*mm*, heat loss effect seems clearly to dominate the combustion resulting in pressure drop and reduction of available work. In terms of combustion efficiency, chamber height does not seem to affect much in millimeter scale. This means the effect of combustion efficiency itself does not vary in such dimension. From the data we have collected from the combustion experiments, the chamber height of micro engine has been determined to be 1*mm* in depth.

DESIGN OF MICRO COMBUSTION ENGINE

Structure of Microengine

Based on the combustion test, the micromachined internal combustion engine has been designed as shown in Fig. 5. The proposed micro engine is composed of three layers:
1) engine body which includes combustion chamber, piston

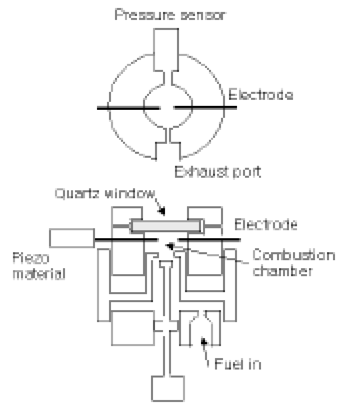

Figure 2. **Schematic of variable depth combustor upper and side view**

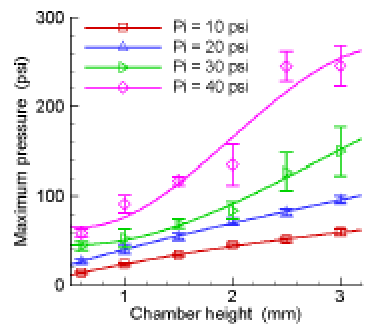

Figure 3. **Maximum pressure obtained in all test cases**

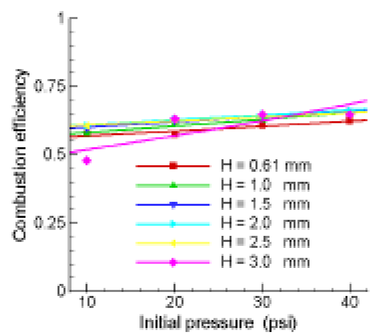

Figure 4 **Combustion efficiency defined by the ratio of reversible work to ideal heat production in each test case**

cylinder, and spark plugs; 2) engine cover which includes gas inlet and gas exhaust holes; and 3) engine bottom which composes a wall of engine. In the engine body, fuel passes through the fuel chamber first and then is introduced to the combustion chamber. The anti-flameback channel is located between the fuel chamber and the combustion chamber for prohibiting flameback as shown in Fig. 6.

Operation of Microengine

Operation of microengine is simple and similar to that of a two-cycles-engine as shown in Fig. 7. Fuel is injected into the fuel chamber through the gas inlet hole and passes through the anti-flameback channel and arrives at the combustion chamber. Fuel is then ignited by a spark plug and explodes. From the explosion, pressure is generated in the combustion chamber, moving the piston and compressing the fuel in the other chamber. Finally, the burnt fuel is swept out through the exhaust hole by the flow of new fuel introduced to the combustion chamber in the opposite side.

Sizing of Microengine

The thickness of engine body is 1*mm*. The size of combustion chamber is 1*mm* x 1*mm* x 1*mm* (W x L x H) in order to have a larger size than the quenching distance (0.61*mm*) of hydrogen gas. On the contrary, the anti-flameback channel has 300µm in width which is much smaller than the quenching distance in order to protect the flame from going against the current of fuel. The size of piston is 1.98*mm* x 2*mm* x 1mm (W x L x H), and the length of piston cylinder is 10*mm*. Thus, the movable displacement of piston is 8*mm*. The gap between two spark plugs is 500µm and its thickness is 40µm .

FABRICATION

Engine Body

Fabrication processes are shown in Fig. 8. Combustion chambers, fuel holes, and piston cylinders are patterned into photosensitive glass by a 300nm UV light. Chromium on quartz is used as a mask for UV light. The energy density needed for patterning throughout 1*mm* thick glass is about $4J/cm^2$. After UV exposure, heat treatment is needed for crystallization of the exposed area. The heat treatment condition is given in Table 1. Then, the shallow etch of the exposed area is needed for use as an alignment key when patterning spark plugs. Now, Cr/Au is deposited as a seed layer for electroplating. Thick PR (AZ 9260) is coated and patterned to be used as a mold for nickel electroplating. The electroplated spark region is held up from neighbor region and this becomes the leakage path. To reduce this leakage path, the perimeter of piston cylinders is electroplated at the same time with the cathode of spark plugs. But there is enough space to protect shortage and discharge between the electroplated perimeter of piston cylinder and the spark anode. After nickel is electroplated, PR is removed in acetone. Diluted HF solution (DI:HF=10:1) is used as etching solution of the exposed glass. The paraffin is used for protection during the etching procedure. Finally, Cr/Au seed layers are removed.

Engine Cover

The engine cover is composed of two layers. One has fuel inlet holes and exhaust holes. The other has the upper combustion chamber to provide the sufficient space for fuel combustion. Each layer of engine covers is made independently and then fusion bonded together. .

Integration

Fabricated engine cover, engine body, and engine bottom have been bonded together using high temperature epoxy. The picture of the fabricated microengine is shown in Fig. 9.

Ramp Rate	Room Temperature -> 500°C : 3 °C /min
Dwell Time	500 °C : 1 hour
Ramp Rate	:500 °C -> 600 °C : 1 °C/min
Dwell Time	600°C : 1hour
Cooling Time	600 °C -> Room Temperature : 3 °C/min

Table 1. **Heat treatment condition of photosensitive glass**

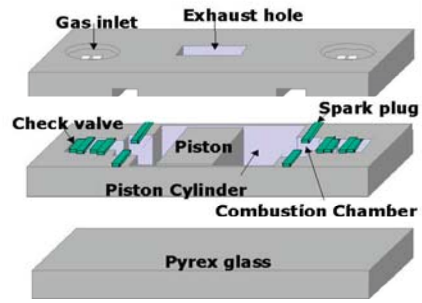

Figure 5. **Schematic view of the micromachined reciprocating engine**

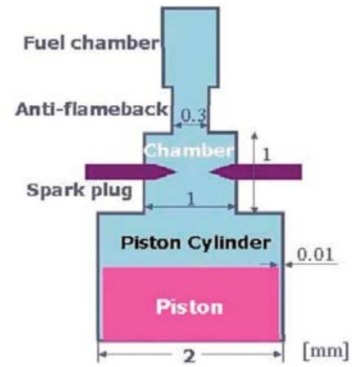

Figure 6. **Size details of the micromachined engine**

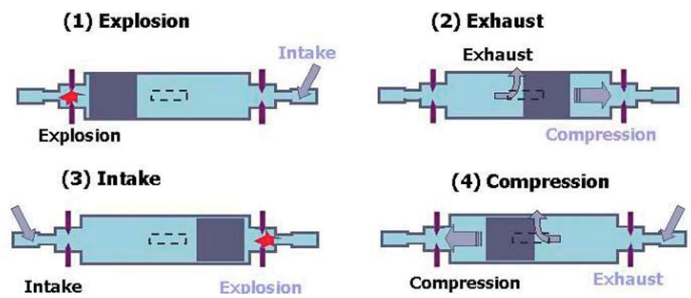

Figure 7. **Operation sequence of the micromachined engine**

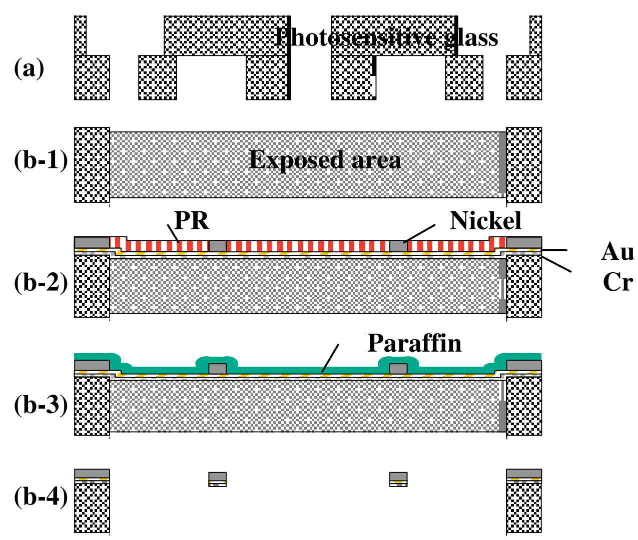

Figure 8. **Process sequence: (a) Engine-cover: fusion bond of two photosensitive glasses, (b-1) Engine-body: UV exposure, heat treatment, and shallow etch for alignment, (b-2) seed metal deposition (Cr/Au), electroplating with PR mold (AZ9260), (b-3) protection of electrodes with paraffin, (b-4) glass ceramic etch with 10% HF.**

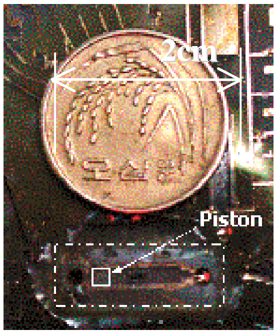

***Figure 9*. Picture of the fabricated micromachined engine**

TEST RESULTS AND DISCUSSION

To validate the reciprocating device, actual combustion test has been carried out on the fabricated prototype microengine. The fuel used for combustion test is premixed hydrogen and air gas (27:73). Flyback-type coil ignition system is used to make the high voltage for spark plugs. Fig. 10 shows the pictures taken from a high-speed snap-shot camera during combustion test. In Fig. 10, the flame is found in the combustion chamber and the movement of the piston has been monitored. After the one-shot combustion, the displacement of piston is 2.7*mm*. By using the data obtained from the combustion test of variable-depth combustors, we can evaluate the displacement of piston.

If this micro engine is assumed as an ideal two-cycles engine without leakage path, then we can apply the OTTO cycle for the fabricated micro engine where isentropic relation, PV^{γ} =constant, is maintained. From Fig. 3, the maximum pressure obtained in the given chamber size is about 1.8 times as large as the initial pressure. In this combustion test condition, the initial pressure is 1 atmospheric pressure; therefore, the maximum pressure after combustion is 1.8 atmospheric pressures. From Fig. 11 (OTTO cycle), we can estimate the displacement of the piston is about 2.1*mm*. This is very similar to the measured displacement, 2.7*mm*. The result of one-shot combustion test shows that the combustion in this micromachined engine can generate a movable power as can be estimated. However, this micromachined engine has some problems. Especially, the leakage of the compressed fuel and the heat loss are the major problems. In order to reduce the pressure drop from leakage, the improved engine should be fabricated using the fusion bonding technology. For quantitative diagnostics, monolithically implanted micro pressure sensors seem promising but are not applied in the present study.

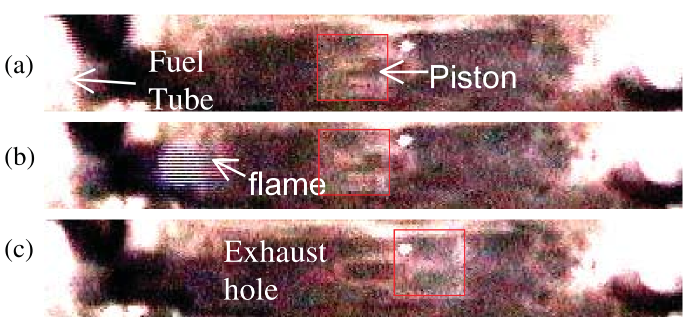

***Figure 10*. Consecutive pictures showing successful combustion and piston movement: (a) initial state, (b) ignition (C) final state.**

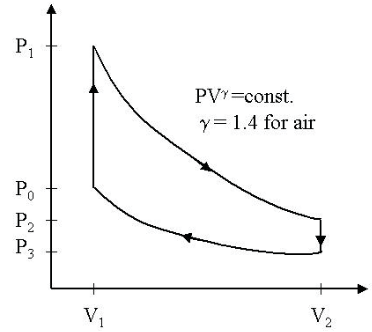

Figure 11. OTTO cycle

CONCLUSIONS

A MEMS reciprocating micro combustion engine has been proposed, designed and fabricated. The design guidelines have been based on the data obtained from the test of variable-depth combustors. Simple pressure measurement and visualization of the test combustor has provided valuable information on micro combustion design, especially on scaling the dimension of microengine for proper operation. We have successfully fabricated the micro combustion engine and demonstrated one-shot combustion test which shows that the combustion in the fabricated prototype engine can generate a movable power. Although the test has been plagued with leakage problem aforementioned, it demonstrates that such a reciprocating micro device can be built and enough power can be generated comparable to theoretical estimation. The findings of the present study warrant further research on micro combustion phenomena and different concepts of micro engines. If further reduction of combustion chamber size is required, additional measures such as preheating the combustible gases and better insulation are needed. As for fabrication processes, better bonding method between glass layers is desirable to eliminate gaps and gas leakage.

ACKNOWLEDGEMENT

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REFERENCES

[1] Mehra A., Ayon A. A., Waitz I. A. and Schmidt M. A., "Microfabrication of High-Temperature Silicon Devices Using Wafer Bonding and Deep Reactive Ion Etching," *IEEE Journal of MEMS*, Vol.8, No. 2, 1999 152-160.

[2] W. Lindsay, D. Teasdale, V. Milanovic, K. Pister, C. Fernandez-Pello, "Thrust and Electrical Power from Solid Microrockets",*in MEM'01*, pp. 606-610

[3] Fu K., Knobloch A. J., Cooley B. A., Walter D. C., Fernandez-Pello C., Liepmann D. and Miyaska K., "Microscale Combustion Research for Applications to MEMS Rotary IC Engine," *Proceedings of ASME 35th National Heat Transfer Conference*, NHTC2001-20089, 2001.

[4] Dan S. Kercher et al. "An experimental study of microfabricated nickel spark plugs", *Transducer*, pp 1412-1415, June 1999

[5] Turns S. R., 1996 An Introduction to Combustion*,* McGraw-Hill. p236.

[6] Lee D. H., Choi K. H. and Kwon S. "Measurement and Modeling of Combustion in a Microcombustor," *36th Thermophysics Conference, AIAA* 2001-3077, 2001.